

An Experimental Investigation of Active and Passive Control of Rotating Stall in Axial Compressors

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Abstract

This paper presents results to date from on-going analytical and experimental investigations of passive and active control methods for suppression of stall in axial flow compressors. The passive control method involved inclusion of flow separators in the inlet and outlet ducts of the compressor. The active control methods investigated included bleed valve modulations, flow recirculation from plenum bleed to inlet of the compressor and fuel flow modulations. It was found that in contrast to theoretical expectations, the use of separators in the inlet and/or outlet ducts did not prevent the onset of rotating stall. However, it was found that with proper number of separators, the onset manner of the rotating stall was tempered. Experimental results to date indicate that it is possible to significantly suppress the onset of rotating stall through a combination of passive and active control schemes, and thus, extend the useful operational range of a compressor.

1. Introduction

The aerodynamic instabilities of surge and rotating stall impose limits on the operating range of compressors in turbine engines. Surge is characterized by global axial oscillations of mass flow and plenum pressure. Rotating stall is manifested as a local, circumferential non-uniform flow within the compressor, which arises from local blade stall in the annular flow area. Though the phenomenon of rotating stall was well known for quiet long time and was extensively considered,¹⁻³ a model that clearly explained the physical fundamentals and the one that could be used for development of control strategies was not established until 1985 by Moore and Greitzer.^{4,5} This model, which came to be known as Moore Greitzer model (MG model), was used by Abed and Lieu⁶ to show that 1D global actuation could suppress the 2D rotating stall with quadratic feedback of the rotating stall amplitude. It was later shown that better performance could be achieved with linear and sub-linear feedback of the rotating stall amplitude.⁷

Earlier works^{8,9} demonstrated control with bleed valve actuation on a small scale low speed axial compressor followed by more recent demonstration in a large scale three-stage low speed compressor¹⁰. However, more recent studies¹¹ on a laboratory compressor found that rate and in particular, magnitude limit the effectiveness of global 1D bleed valve actuation for the control of rotating stall. It is apparent that the use of significant bleed in a realistic engine would involve proper adjustment of fuel. Moreover, one may consider the modulation of fuel rate as an actuation by itself that could be used to suppress rotating stall and surge. If this is proven to be true, it offers a great advantage to the prospect of advanced gas turbine engine control as various aspects of combustion control such as control of NOx emissions and acusto-combustion instabilities can be addressed along with compressor control in a single framework.

As part of the Multi-University Research Initiative (MURI) on Intelligent Turbine Engines program at the Georgia Institute of Technology, a combination of analytical and experimental investigations have been carried out over the last three years using the Laboratory for Identification and Control of Complex Highly Uncertain Systems (LICCHUS) axial compressor facility. The investigations included both active and passive methods for suppression of rotating stall and surge in axial flow compressors. This paper summarizes important findings from those investigations. Under the passive methods, the effectiveness of inclusion of flow separators in front of the compressor in reducing rotating stall amplitude was explored. Under the active control investigations, three schemes were investigated, two of which used bleed valve in the plenum. In the first scheme, bleed air was discharged to the ambient, whereas in the second scheme, bleed air was recirculated to the front of the compressor. The third actuation scheme utilized fuel modulations to a burner located inside the plenum. The control schemes investigated included a linear rotating stall amplitude feedback controller⁷ as well as a fuzzy logic controller¹².

II. Axial Compressor Facility

All experiments have been performed on the Georgia Institute of Technology LICCHUS low speed axial compressor which provides 1.3% pressure rise at 10000 RPM and is capable of rotating stall. A schematic of the rig is shown in Fig. 1 and the main compressor parameters are shown in Table 1.

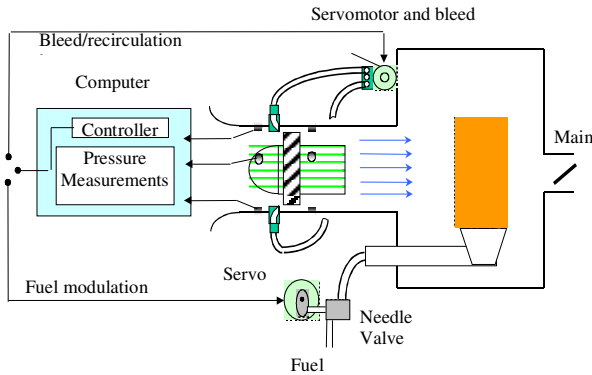


Figure 1. Schematic of Experimental Set-up.

Table 1. LICCHUS Axial Compressor Parameters.

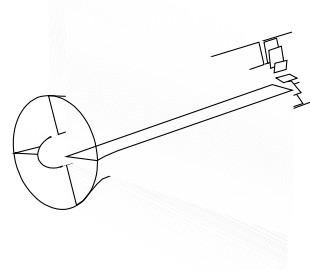
Compressor Design Parameters	Rotor	Stator
Aspect ratio	0.272	0.332
Chord length	0.055m	0.045m
Stagger angle	40.6°	28.6°
Camber angle	37.2°	55.0°
Number of airfoils	7	9
Solidity	1.44	1.52
Pitch	0.0381m	0.0297m
Axial spacing	0.010m	
Tip diameter	0.115m	
Tip clearance	1.39 (% of chord length)	
Hub-tip ratio	0.74	
Nominal rotor speed	10600 RPM	

The plenum has two exit throttle valves. The main throttle is used to bring the system into the nominal operating point and the smaller "bleed" throttle valve is operated as an actuator for active control. The outlet of the bleed valve can be channeled either to ambient or recirculated via circumferentially distributed tubes to the compressor inlet. The plenum contains a propane diffusion flame burner with fuel supply that is controlled by a servo valve. This simplified system displays the important features of an axial compression system, such as rotating stall and surge, and the coupled compressor-combustor dynamics.

III. Results and Discussion

III.1. Passive Control Schemes

First, a passive control method was considered in which the objective was to improve the performance of the compressor without feedback or actuation. The theory behind the MG model⁴ implies that the rotating stall which is manifested as traveling waves around the compressor circumference induce variation in the lateral velocity at each circumferential location. Thus, seemingly, the theory suggests that if lateral velocity is blocked at one or more circumferential locations along the inlet and/or outlet using separators (as shown in Figure 2), traveling waves cannot develop. This in turn should allow the compressor to operate along the axis-symmetric branch even when the slope of its characteristic map is positive, a zone which under regular conditions would give rise to the growth of rotating stall rendering the axis-symmetric branch unstable. This idea had been reached independently by one of the authors. Following an extensive patent search, it was found to



be offered by Moore¹³ on the very same theoretical ground. The inventor was so sure about the effectiveness of the separator that he protected an invention for a single inlet separator claiming that, while more separators could be used for symmetry, they were not needed for rotating stall suppression.

Figure 2. Flow Separators in the Inlet.

Figure 3 shows the time trace of signals (vertically shifted for comparison) obtained from three static pressure transducers placed at the inlet duct at equal angular intervals. The main throttle position was selected for a rotating stall condition. The solid lines indicate the pressure trace with no flow separators and the dotted lines indicate the values with one flow separator along the entire inlet duct. Figure 3 shows that the amplitudes of the pressures with and without one separator are similar and they are travelling with the same speed. This would indicate that the single separator had hardly, if at all, altered the flow pattern of the circumferential perturbation. This result is not

yet fully understood and it is currently under investigation.

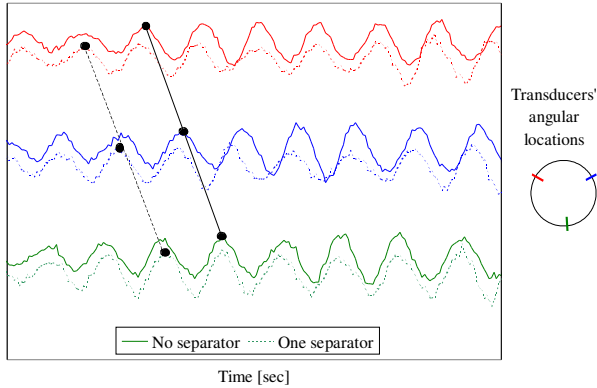


Figure 3. Time Trace of the Steady Rotating Stall Static Pressure Data at Three Circumferential Positions with and without a Flow Separator.

Next, the inlet was modified with different number of separators. It was found that, while not capable of eliminating the rotating stall, increased number of separators could delay somewhat the onset of rotating stall and moderate its amplitude. Figure 4 shows the effect of the inclusion of eight inlet separators on rotating stall. The rotating stall, which is nearly zero for throttle opening above some critical value, which is known as the stall inception point, jumps abruptly for throttle openings below this point. Figure 4 indicates that with eight separators, the rotating stall amplitude is smaller. It was reasoned that such a passive means might not suffice by itself but could be used in conjunction with an active scheme to augment its performance. Figure 4 shows the performance of a feedback controller (in this case, a fuzzy logic controller¹²) scheme with and without flow separators. While the active scheme itself will be discussed in the next section, it is important to note the enhanced performance of the combined active and passive means.

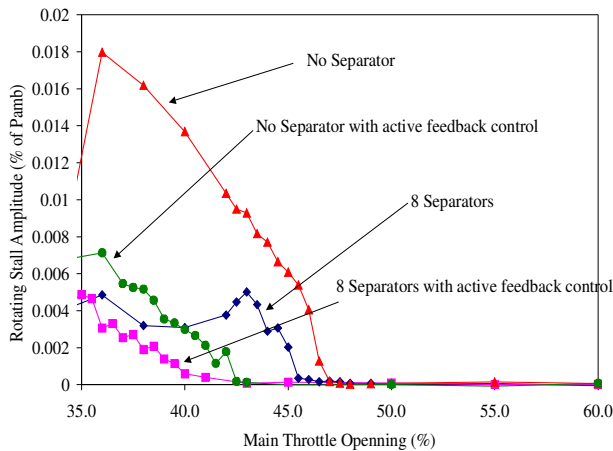


Figure 4. Effect of Eight Flow Separators on Rotating Stall in a Passive Scheme and Combined with Active Scheme.

III.2. Active Control with Flow Recirculation

The basic idea behind 1D global actuation schemes investigated in this study is to keep the average flow through the compressor above the critical flow below which the compressor blades will stall. A commonly considered way of achieving this is by bleeding air from the back of the compressor, i.e., the plenum, so as to cause pressure gradient that will tend to increase the flow through the compressor. In this study, we considered two schemes; bleed air to the ambient scheme and plenum-inlet recirculation scheme in which bleed air is returned to the compressor inlet. A schematic of the two approaches is shown in Figure 5. The authors maintain that recirculation rather than ambient bleed holds the key to successful implementation of active stall control in realistic compressors. However, an in-depth discussion of this aspect is not included here due to space limitations of the paper. In the discussion that follows, it is important to notice a basic difference between the two schemes. In the ambient bleed scheme, the flow through the inlet duct is unaffected by the application of the bleed, which rather decreases the flow that enters the combustor. On the other hand, in the recirculation scheme, the flow into the combustor is equal to the flow in the inlet duct and the returned air, if properly bled, is used to relieve the load on the compressor. This difference becomes apparent when the performance of the two schemes are examined using the inlet flow as the independent variable (see Figs 6, 9 and 10).

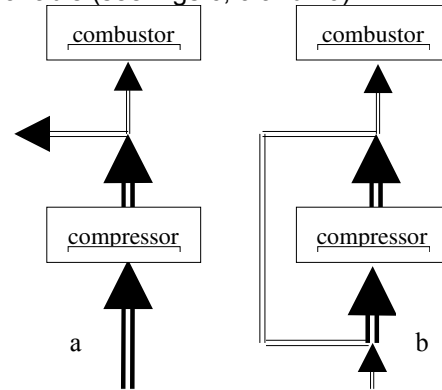


Figure 5. Schematic of Flow Paths with (a) Ambient Bleed and (b) Recirculation.

Figure 6 shows the variation of rotating stall amplitude as a function of the inlet mean mass flow rate (normalized with respect to blade tip speed and duct area) for both ambient bleed and recirculation bleed with 50% and 100% bleed valve openings. In this experimental set-up, the mass flow rate at 100% bleed valve opening is about 60% of the mean

compressor mass flow rate at the rotating stall inception point. Figure 6 shows that applying bleed recirculation delays the onset of rotating stall and the delay increases with the magnitude of recirculation. It should be noted that the mass flow rate through the bleed valve is not a linear function of its opening. Notice that as expected, the curves of 50% and 100% ambient bleed lie almost on top of each other. Although recirculation delays the stall inception point, it also causes reduction in the flow into the combustor, and thus, altering the designed operating point of the compressor. For this reason, one should not consider usage of a constant recirculation or ambient bleeding. Rather, it should be applied only when the compressor is on the verge of stall in conjunction with feedback control. Since the effective opening area of the bleed valve could hardly be changed around the closed position, i.e., 0% position, rendering any closed loop control ineffective, we chose the 50%, rather than 0%, opening as reference point around which closed loop control was applied.

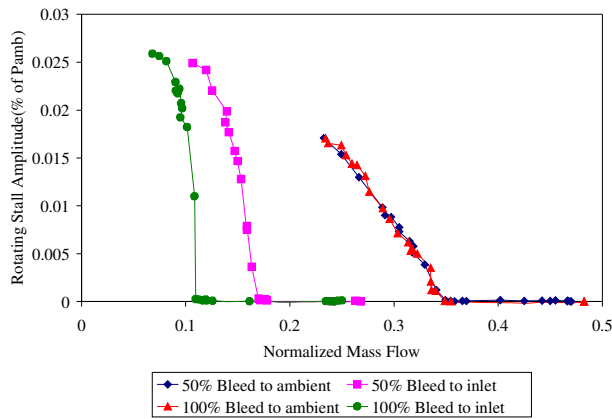


Figure 6. Effect of Flow Recirculation on Rotating Stall for Two Different Bleed Valve Settings.

Figure 7 shows how incorporation of feedback control, in this case a fuzzy logic controller¹², around nominal 50% bleed recirculation extends the unstalled operating range of the system. Note that the closed loop, i.e., with feedback, curve is shifted almost all the way towards the 100% curve. This means that the feedback scheme, which modulates the valve opening about the nominal 50% opening in relationship to the rotating stall amplitude, provides significant suppression of rotating stall.

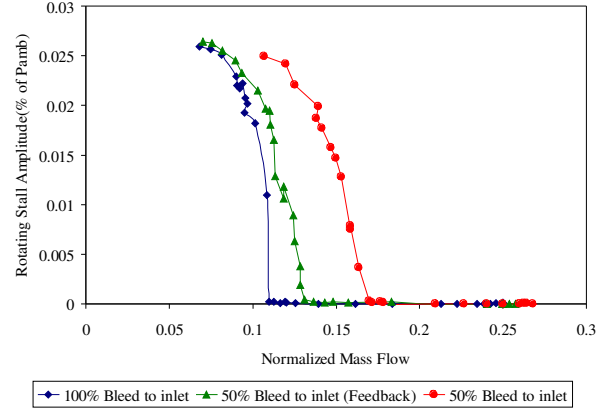


Figure 7. Effect of Flow Recirculation with Active Control on Rotating Stall.

It was suggested that recirculation bleeding should offer advantages over ambient bleeding. The question is whether the introduction of flow into the compressor inlet will not degrade the compressor performance in terms of pressure rise characteristics. To provide a basis for comparison, we first examine the compressor characteristics with ambient bleed, which by its nature does alter the flow through the compressor, and then, we compare them to the characteristics obtained when the bleed air is recirculated to the compressor inlet. Figure 8 shows the dependence of the total pressure rise on the main throttle opening for 0%, 50% and 100% bleed valve openings. The bleed valve openings should, in essence, shift the basic curve to the left. Figure 8 indicates that this indeed is the case.

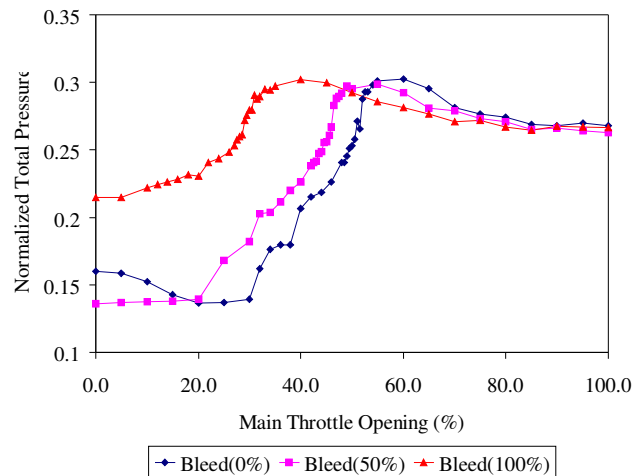


Figure 8. Dependence of compressor pressure rise upon main throttle opening for various opening of the ambient bleeding valve.

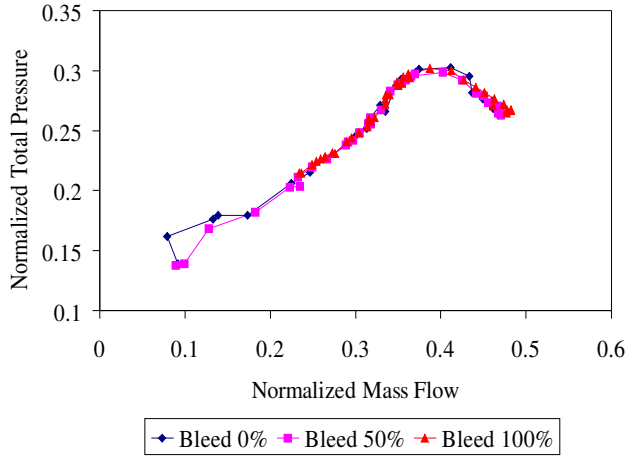


Figure 9. Dependence of compressor pressure rise upon normalized flow rate for various opening of the ambient bleeding valve.

In Figure 9, we re-plot the results of Figure 8 in terms of the normalized total pressure versus the normalized inlet mass flow rate in order to show that ambient bleed merely changes the inlet mass flow rate without having any appreciable effect on the compressor system characteristics. Similar data for the case with flow recirculation is shown in Figure 10. In this case, as expected, different bleed recirculation settings give rise to different curves. What is important is that the curves retain the same basic feature and in particular, each curve has nearly the same maximum pressure rise. Thus, Figure 10 indicates that recirculation does not degrade the aerodynamic performance of the compressor itself.

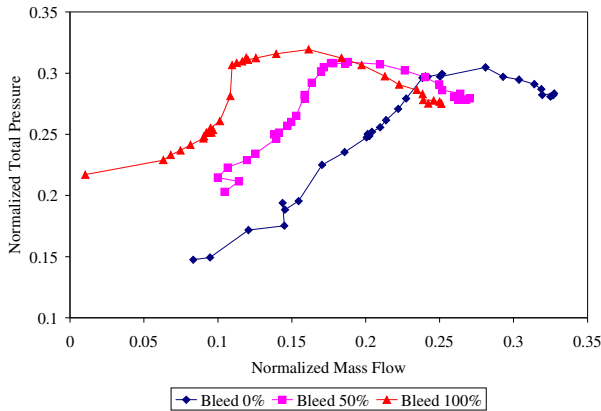


Figure 10. Dependence of compressor pressure rise upon normalized flow rate for various opening of the recirculation bleed valve.

III.3. Active Control with Fuel Flow Modulations

Next, the use of fuel flow modulations is considered. Figure 11 is an analytically obtained bifurcation diagram¹⁴ depicting the variation of rotating stall amplitude with main throttle opening. It is clear from this figure that the effect of fuel flow modulations

is to make the bifurcated branch at the stall inception point supercritical, instead of a subcritical bifurcation. It was shown that fuel modulation is in essence analogous to main throttle change¹⁴. Using the experimental set-up depicted in Figure 1, this analogy was examined.

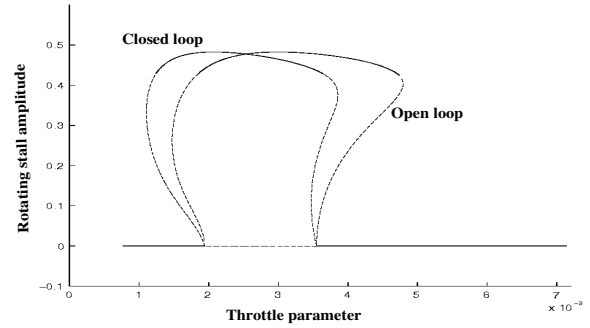


Figure 11. Effect of fuel flow modulation upon the Bifurcation diagram of the compression system.

Figure 12 shows the obtained pressure rise characteristics with no heat addition and with constant heat addition of 20 kW. It is seen in Figure 12 that an increase in heat addition behaves, as predicted, in an analogous manner to a decrease in downstream throttle area, hence, the offset between the two curves. Figure 12 essentially displays that the 20 kW heat addition serves as a second independent variable that defines the operating state of the compressor. This implies that heat addition can be manipulated to set the operating point of the compressor and hence, to control its stall.

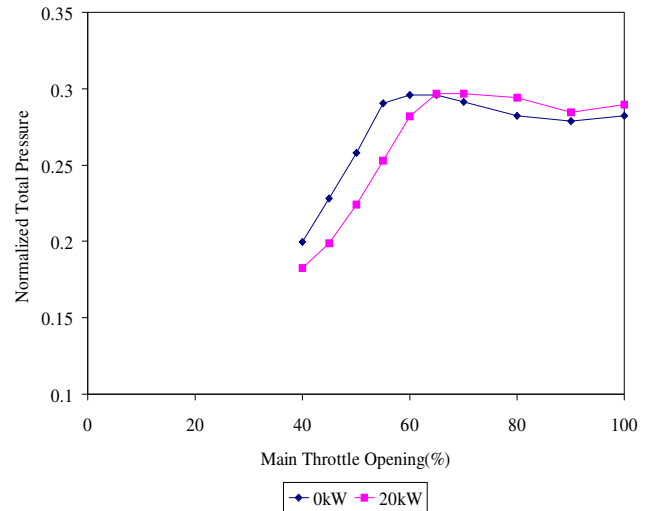


Figure 12. Normalized Total Pressure with Two Different Heat Rates.

IV. Conclusions

Based on the results obtained to date, the following conclusions can be made:

1. The passive control scheme using flow separators with active bleed valve modulations seem to be effective in suppressing rotating stall amplitude significantly. However, the flow separators by themselves do not eliminate rotating stall.
2. It is possible to achieve significant delaying of the onset of rotating stall without significant change in overall performance with flow recirculation scheme.
3. The use of fuel flow control seems to be a viable means for compressor control.

Acknowledgments

This study is funded under the MURI on Intelligent Turbine Engines from the US Army Research Office under contract No. DAAH049610008. The help received during modifications to the experimental set-up from Mr. G. Carbonneau is acknowledged.

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